Neutron EDM status @ PSI

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On behalf of the nEDM collaboration @ PSI

51st Rencontres de Moriond

EW session

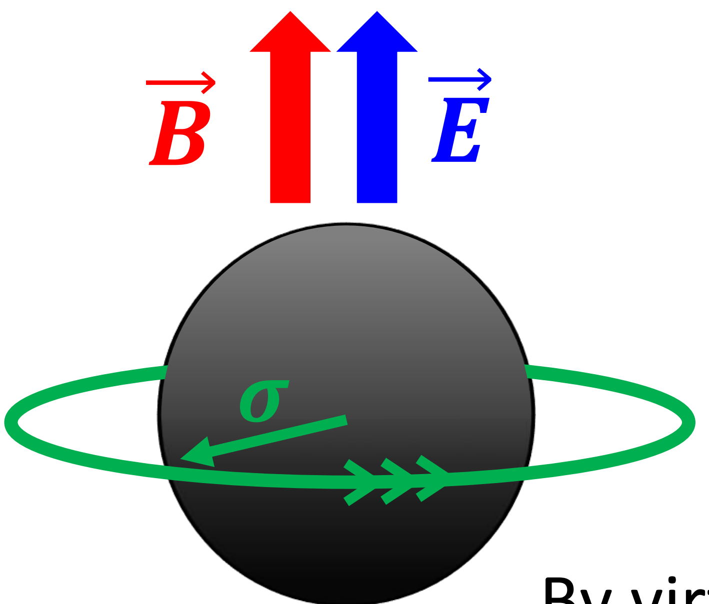
La Thuile, IT

12 – 19 mar 2016

EDM and CP violation

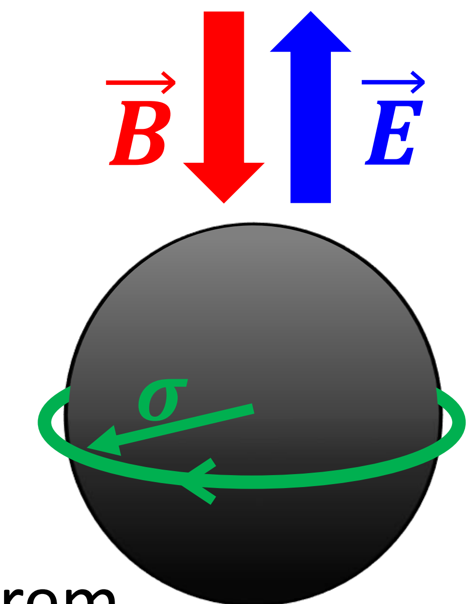
Spin ½ particle
in $\vec{B}$ and $\vec{E}$ fields

$$H = -\mu B\,\boldsymbol{\sigma} - dE\,\boldsymbol{\sigma}$$



Larmor frequency shift :

$$\delta\omega_{\mathrm{L}} = \frac{4}{\hbar}\boldsymbol{d}\cdot\boldsymbol{E}$$



not T invariant

By virtue of the CPT theorem

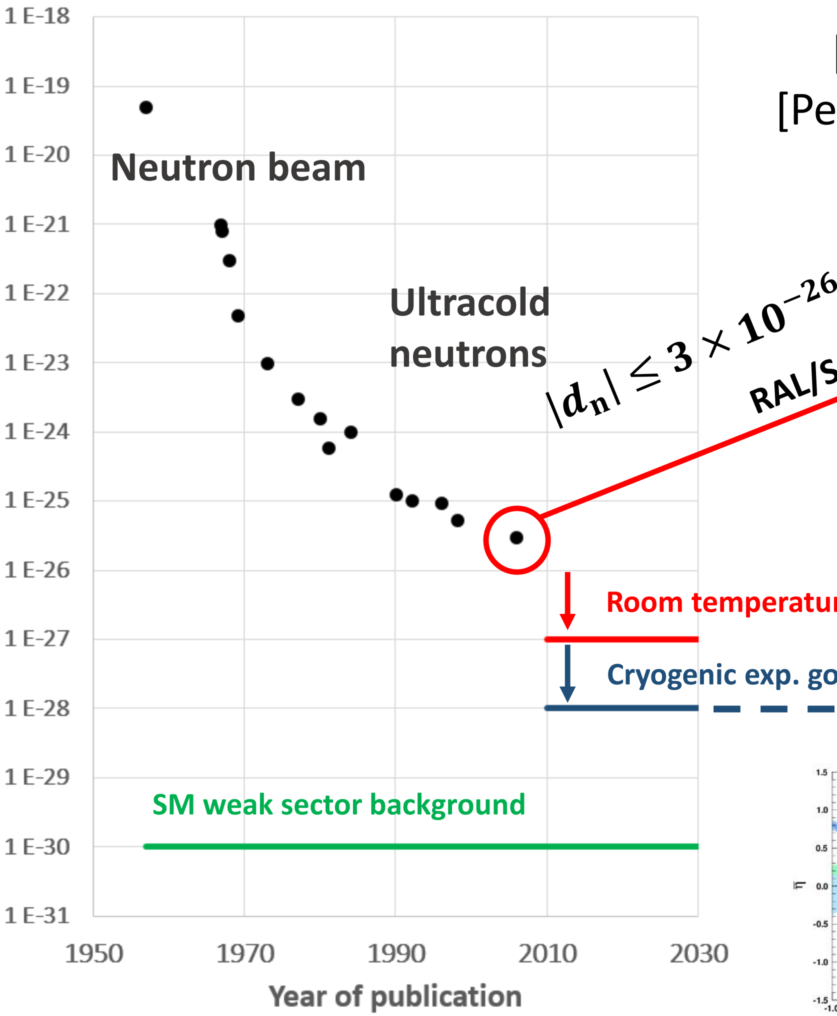
T violation -> **CP violation**

Search for
$E^{\uparrow\uparrow} - E^{\downarrow\uparrow} \sim 10^{-22}$ **eV !!**

High precision
low energy experiment

Where do we stand?

nEDM upper limit (*e*.cm)



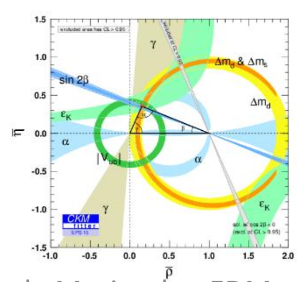
[Baker, 2006]
[Pendlebury, 2015]

$|d_n| \leq 3 \times 10^{-26}\ e.\text{cm}\ (90\%\ \text{CL})$

RAL/Sussex/ILL

Magnetic shield end caps, not pans!

nEDM spectrometer at ILL (Grenoble) before moving to PSI (Villigen) in 2009

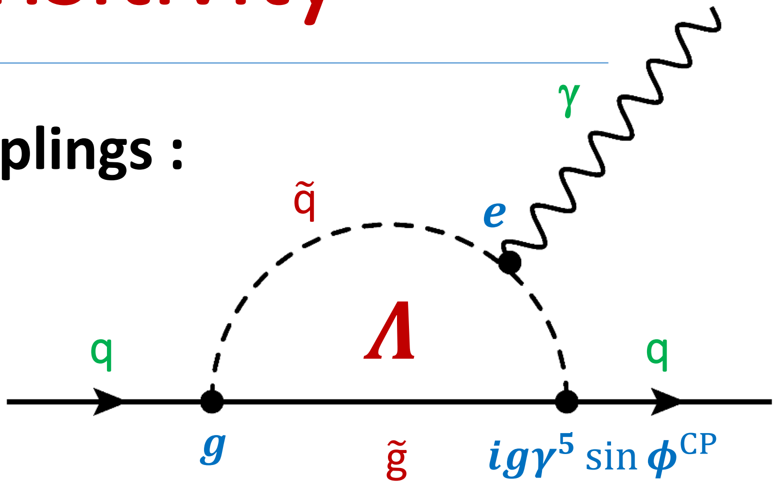


SM strong sector : $\theta_{QCD} < 10^{-10}$

High energy scale sensitivity

1. EDMs arise at 1 loop with BSM couplings :

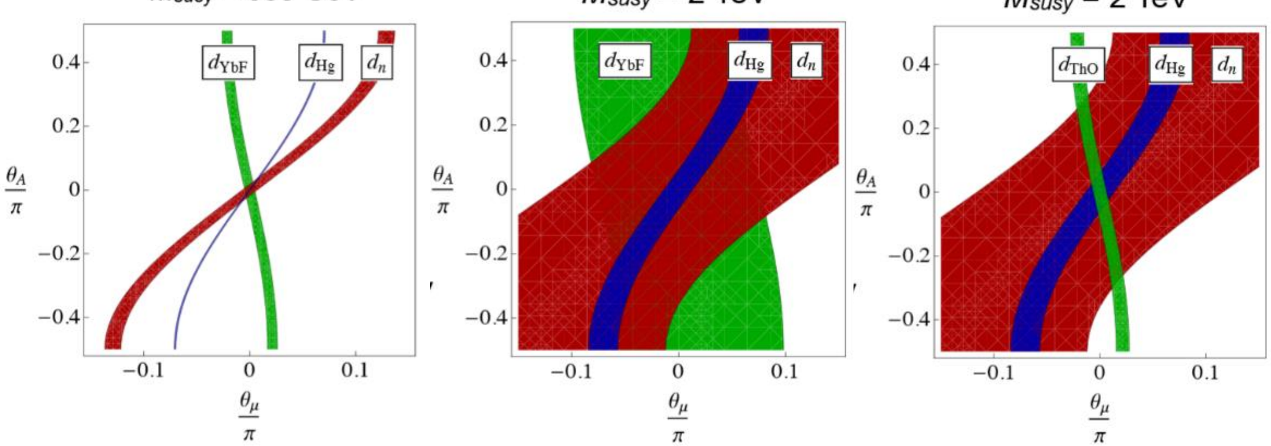
$$d_n \approx 10^{-25} e.\text{cm} \times \sin(\phi^{CP}) \times \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2$$



[Pospelov & Ritz, 2005]

- Balance between : ϕ^{CP} / Λ
- $\sin(\phi^{CP}) \sim 1$ implies $\Lambda > 10$ TeV

2. LHC / EDMs complementarity :



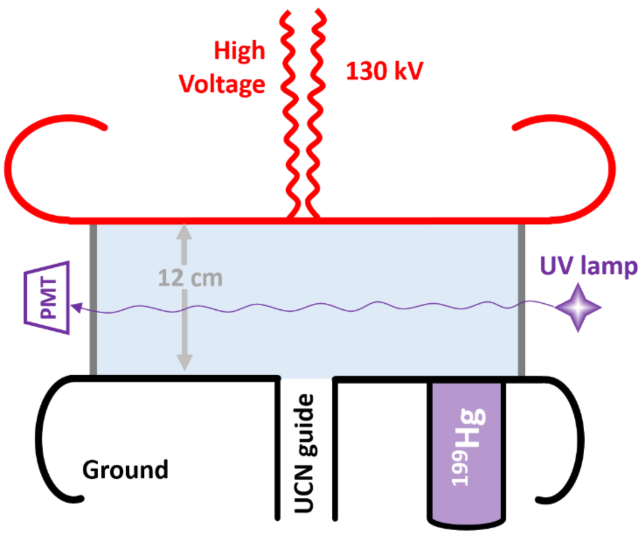
[Ritz, 2015]

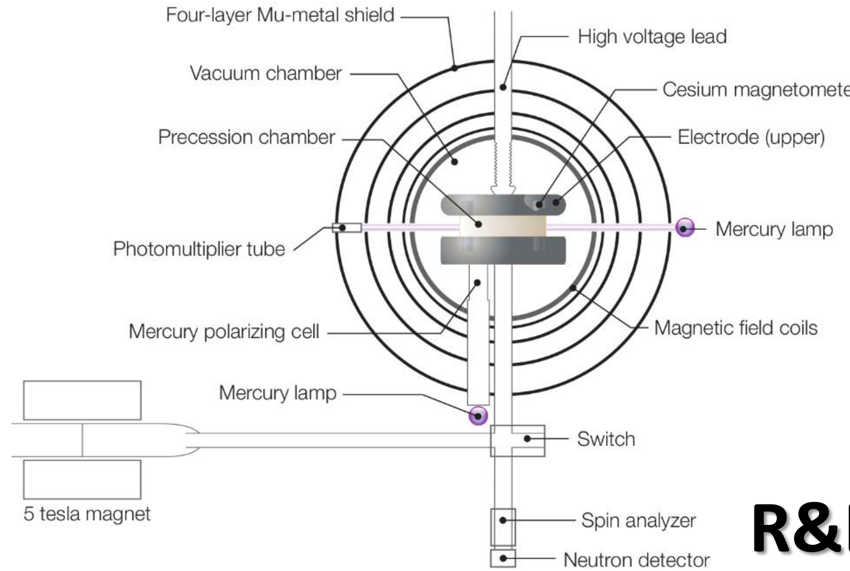
- **Various EDM experiments needed**
- **Testing electroweak baryogenesis scenario**

Experimental setup

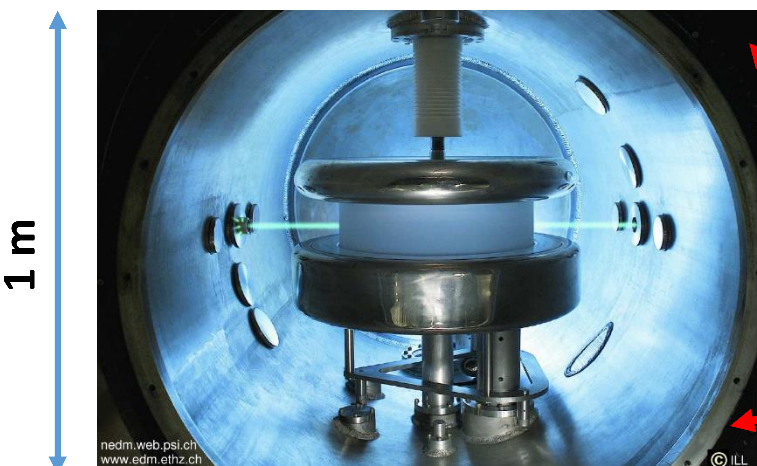
Use of ultracold neutrons (UCN) with $E \approx 100$ neV!

nEDM phase





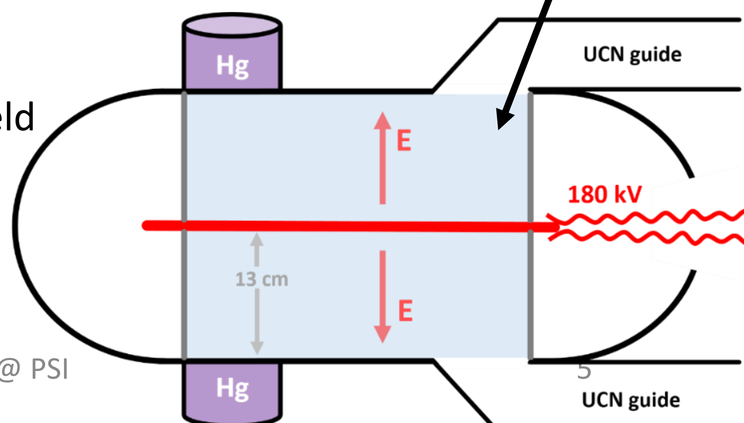
R&D phase



external
4 layers mu-metal shield

$\cos\theta$ coil
$B_z \sim 1\ \mu T$

n2EDM phase

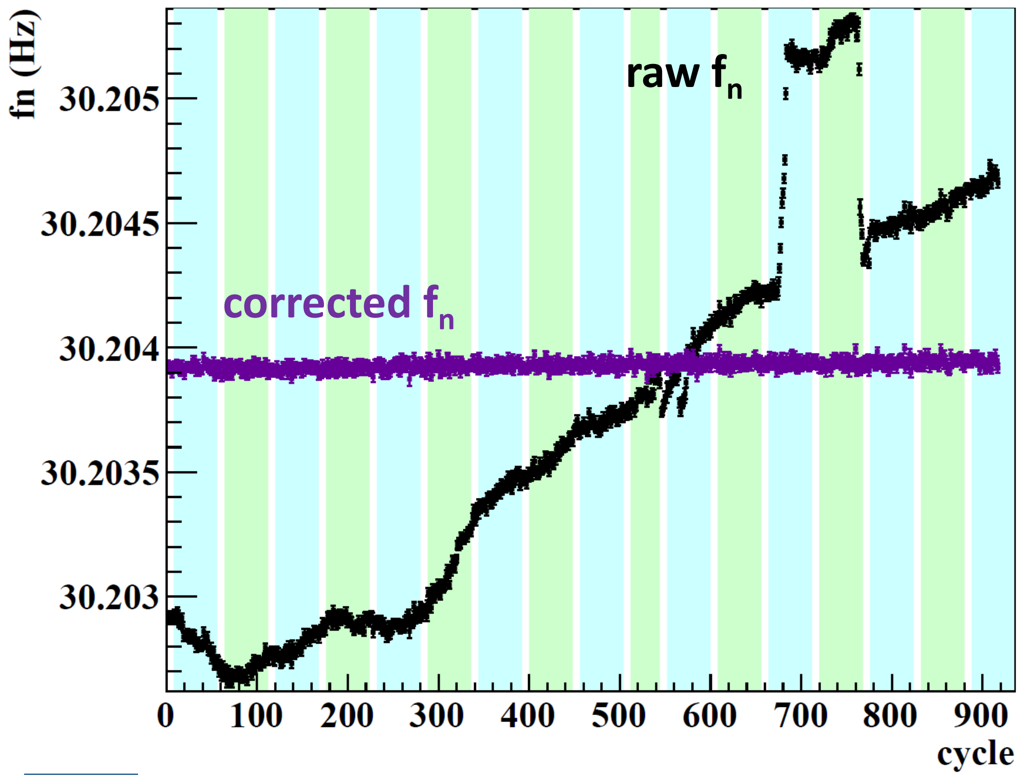


NB: Upgraded RAL-Sussex spectrometer

Challenge

$$\sigma_d^{\text{stat}} = \frac{\hbar}{2E\alpha T\sqrt{N_{\text{UCN}}}\sqrt{N_{\text{cycle}}}}$$

- 10^{-7} B-field **stability** over **200 s**
- 10^{-4} B-field **homogeneity** over a **20 ℓ** volume



$\vec{B}$ & $\vec{E}$ parallel

$\vec{B}$ & $\vec{E}$ anti-parallel

Statistics : $N_{\text{UCN}} \sim 10^4$ **UCN/cycle**

Co-magnetometry allows to be only statistically limited by UCN counting

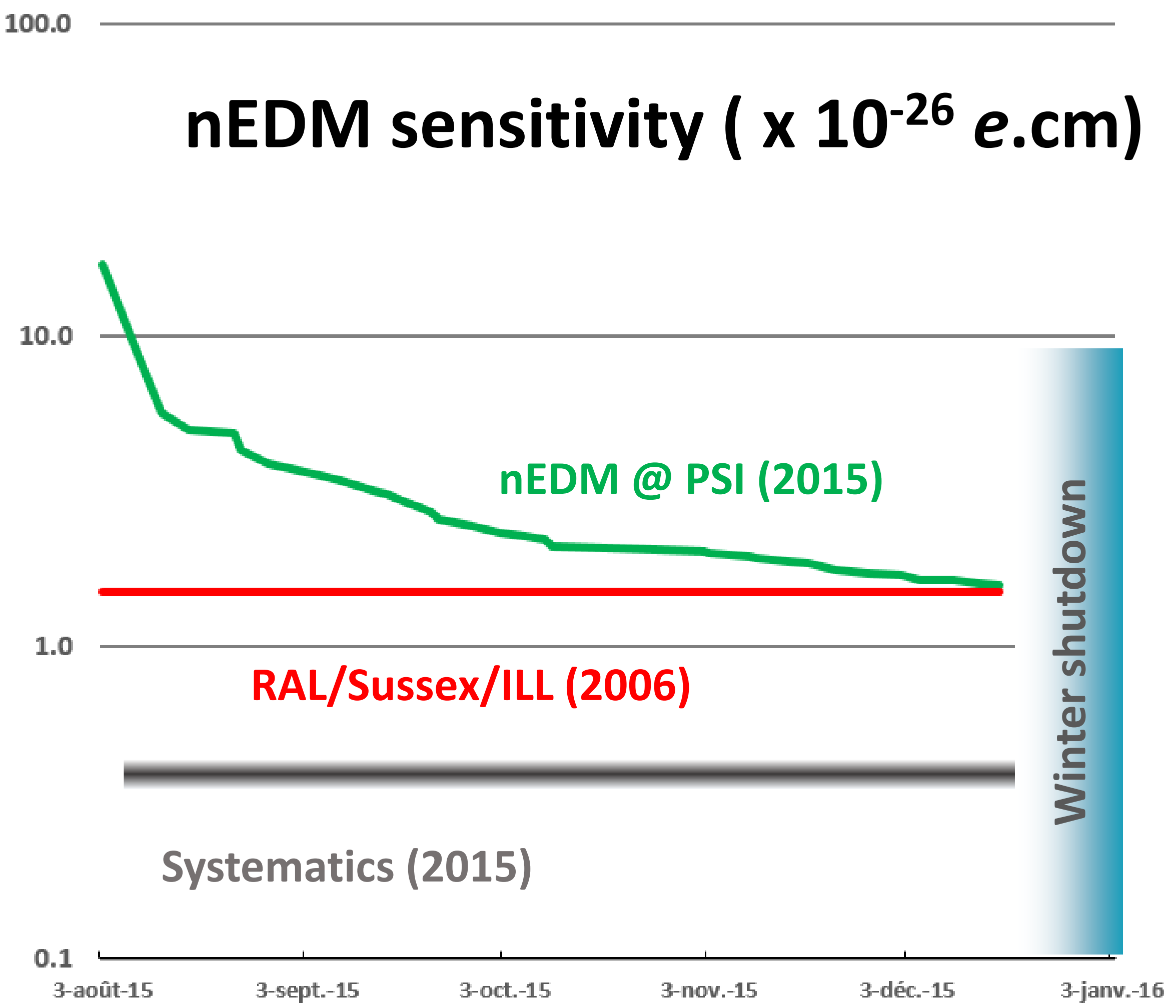
$\boldsymbol{\sigma_d/\text{cycle} = 1.10^{-24}\ e.\text{cm}}$

NB : 1 cycle ~ 5 min of free spin precession

Need to repeat thousands time the measurement to reach

$\boldsymbol{\sigma_d = 1.10^{-26}\ e.\text{cm}}$

Statistical sensitivity



1. The nEDM spectrometer installed at the PSI takes data with the best daily sensitivity.
   2015 cumulated :
   $\sigma_d \approx \mathbf{1.58} \times \mathbf{10^{-26}}$ $e.\mathbf{cm}$

2. nEDM phase goal:
   $\sigma_d \approx \mathbf{1} \times \mathbf{10^{-26}}$ $e.\mathbf{cm}$
   within **one years**

3. n2EDM phase goal:
   $\sigma_d \approx \mathbf{10^{-27}}$ $e.\mathbf{cm}$ **level**
   within the **next decade**

Thank you for your attention

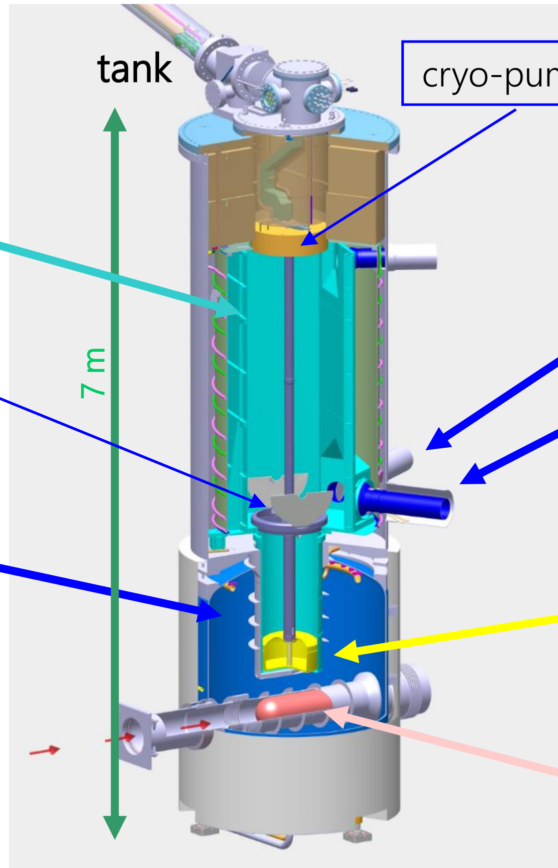
The new PSI UCN Source

DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3

SV-shutter

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

pulsed
1.3 MW p-beam
600 MeV, 2.4 mA,
1% duty cycle



cryo-pump

UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)

cold UCN-converter
~30 dm^3 solid D_2 at 5 K

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

Order of magnitude:

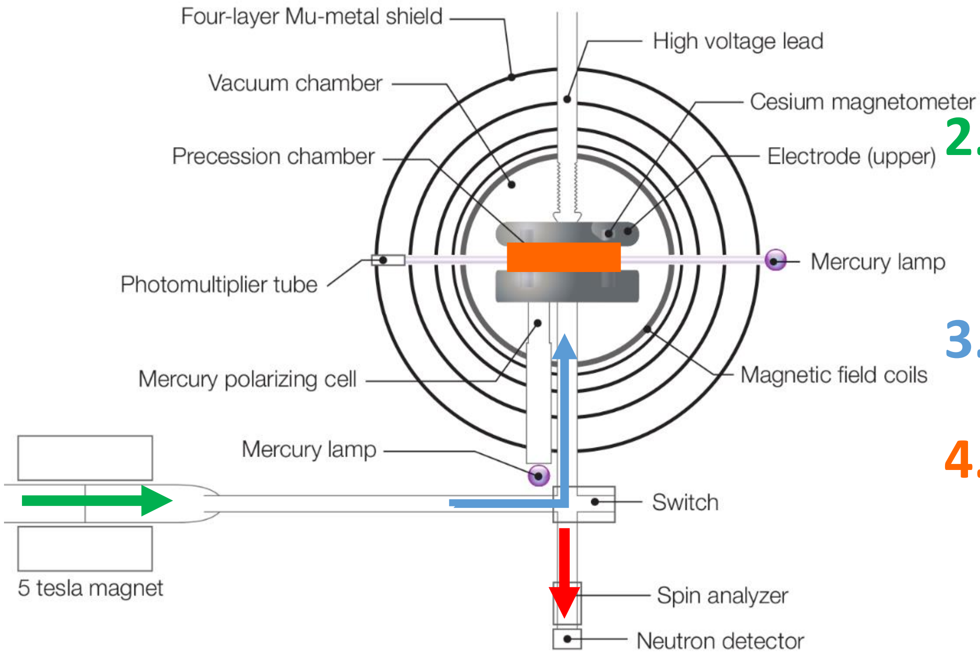
$E_{UCN} \sim 100\ \mathrm{neV}$

$V_{Grav} = m_n g$
$100\ \mathrm{neV/m}$

$V_{Mag} = \mu_n$
$60\ \mathrm{neV/T}$

Experimental setup

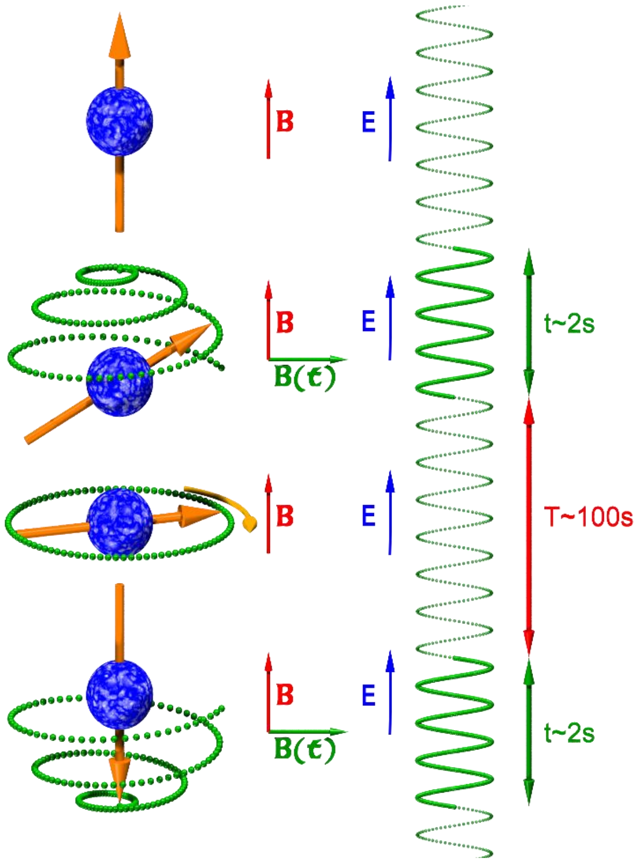
Cycle length : 5 min



$$P(\uparrow\rightarrow\downarrow) \propto \cos\left(\frac{f_{RF} - f_{L}}{\Delta\nu}\right)$$

1. **Production of Ultra Cold Neutrons (UCN) in the new PSI UCN source**
   $E_{UCN} \sim 100\ \mathrm{neV}$
2. **UCN are spin-polarized ↑ with a 5T magnetic field**
3. **Fill the precession chamber**
4. **Store UCN for 200 s with (E, B) parallel or antiparallel**
   1. **Apply $\frac{\pi}{2}$ pulse** **(2s)**
   2. **Spin freely precess** **(200s)**
   3. **Apply $\frac{\pi}{2}$ pulse** **(2s)**
5. **Measure spin Up & Down neutron**

The Ramsey method of separated oscillatory fields



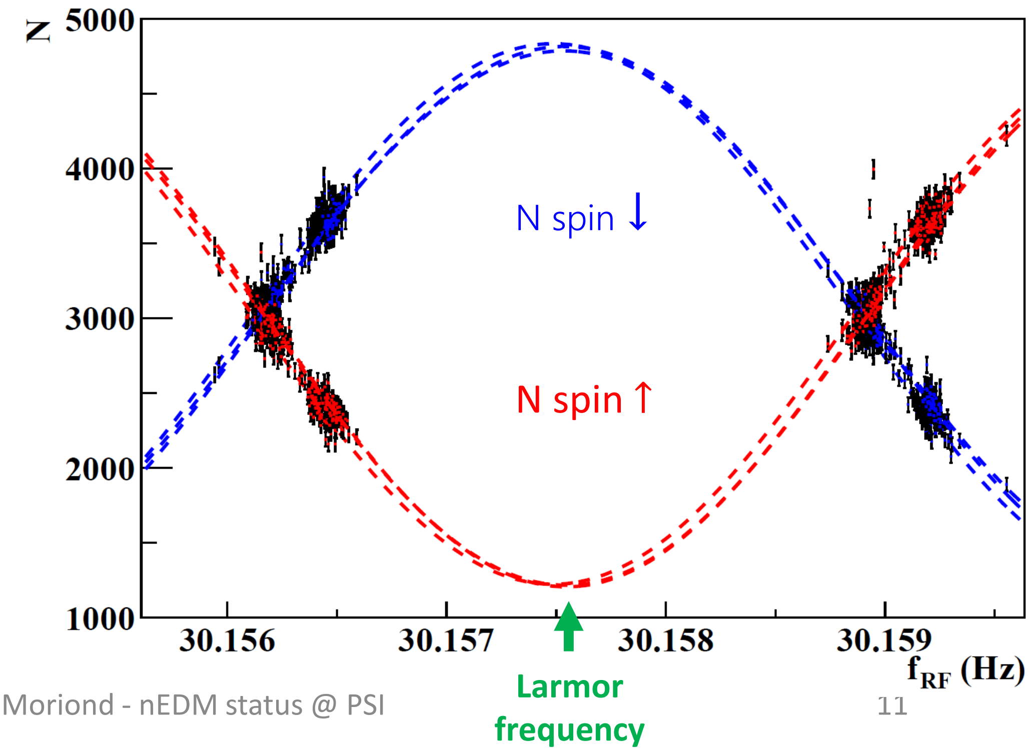
Ramsey cycle

$f_L \approx 30$ Hz in 1 μT

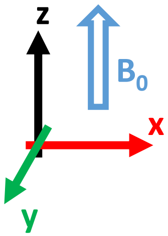
Precision at the ppm level

$$\frac{\sigma_{f_n}}{f_n} = \frac{1}{2\pi\, T_p\, \alpha \sqrt{N_{UCN}}}$$

Fit to the central Ramsey fringe

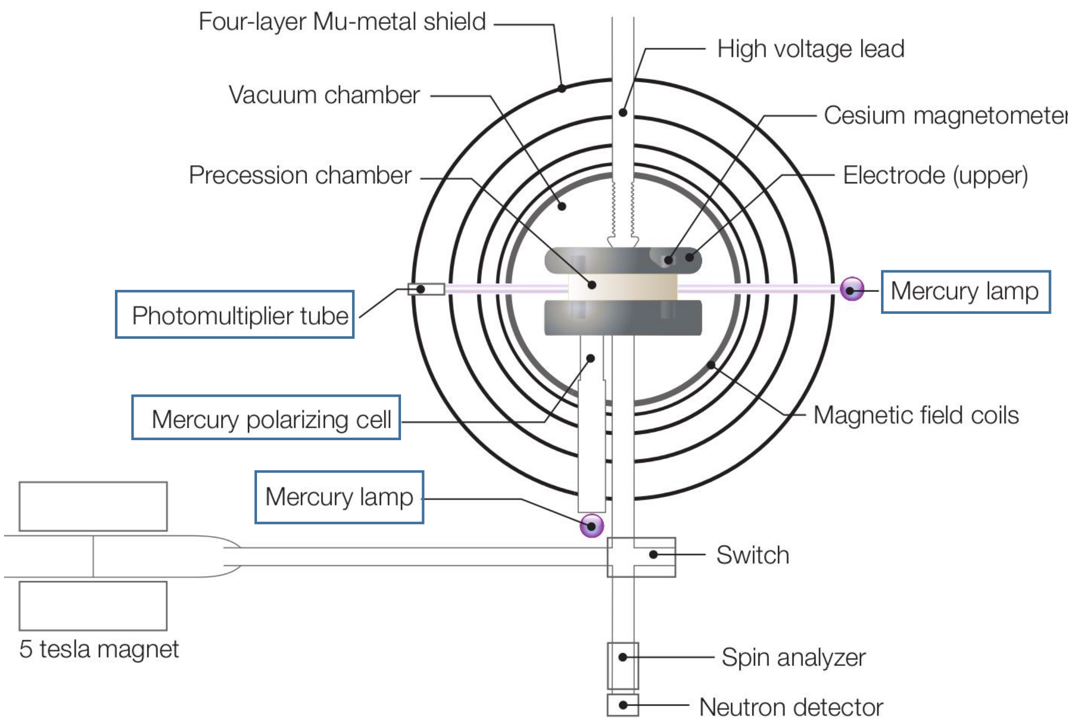


HgM functioning principle



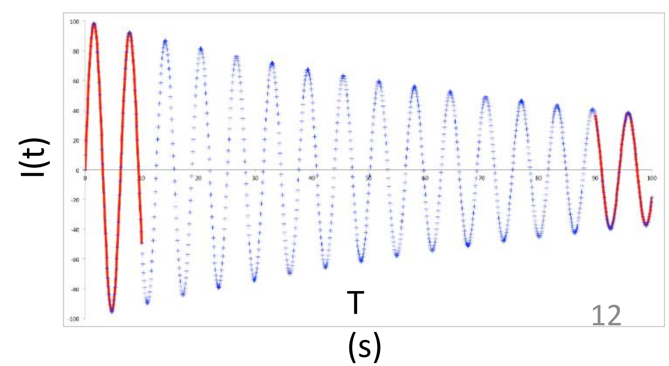
- ^{199}Hg atoms are spin polarized by optical pumping (40s)
- Apply a $\frac{\pi}{2}$ **pulse** (2s)
- Free precession in (x, y) plane (200s)

$$I(t) = Ae^{-\frac{t}{\tau}}\sin(\omega_L t + \varphi)$$

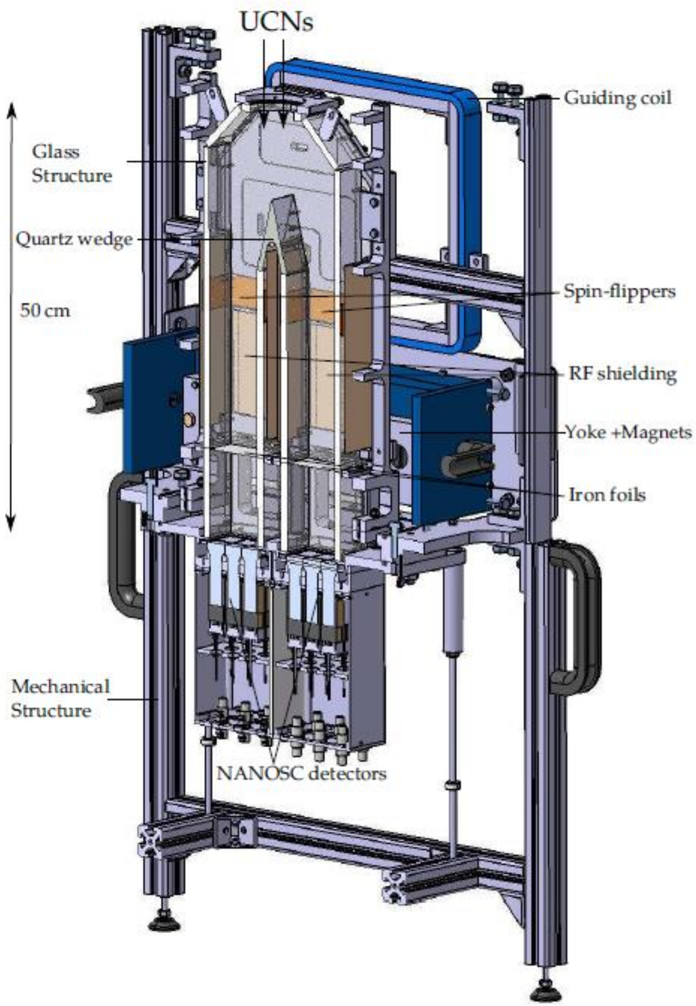


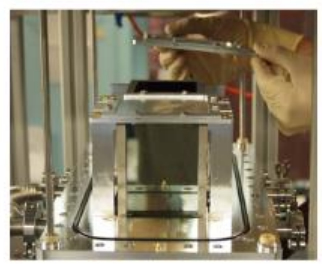
Relaxation time constant due to wall collision ≈ 100 s

Oscillating phase @ Larmor frequency $f_L = \gamma_{Hg} B_0 \approx 8$ Hz



New simultaneous UCN detection





^{6}Li-doped glass scintillator detector

n + ^{6}Li →
^{3}H (2.74 MeV) + α (2.05 MeV)

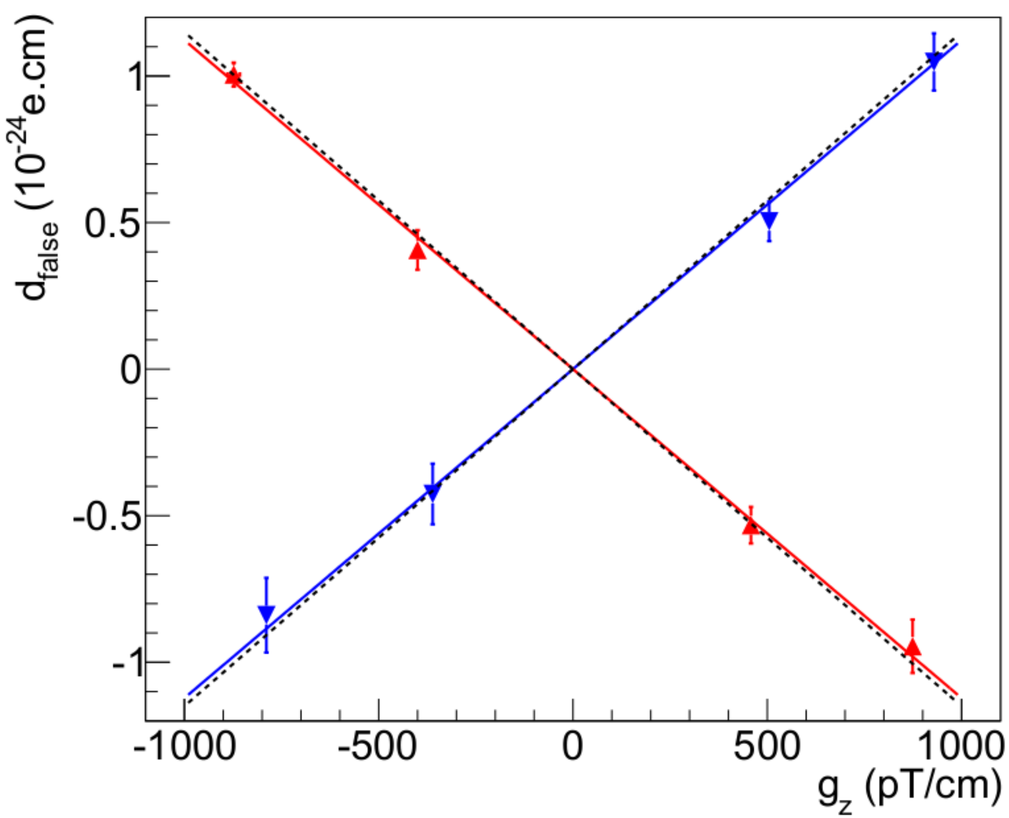
Good discrimination of γ-ray background and deposited energy

Measurement of both spin Up & Down components at the same time

Improvement of 18% in nEDM sensitivity compared to sequential detection

Motional ^{199}Hg induced false EDM

Systematic effect: frequency shift : $\delta\omega(^{199}\mathrm{Hg}) \propto \left(\tilde{B}_{\overrightarrow{\nabla B}}(t) + \tilde{B}_{\vec{v}\times\vec{E}}(t) + \cdots\right)^2$



Data B_0 down

Data B_0 up

Best fit to the data:
$$d_{Hg}^{false}(g_z) = |a| \,.\, g_z$$

Theoretical slope

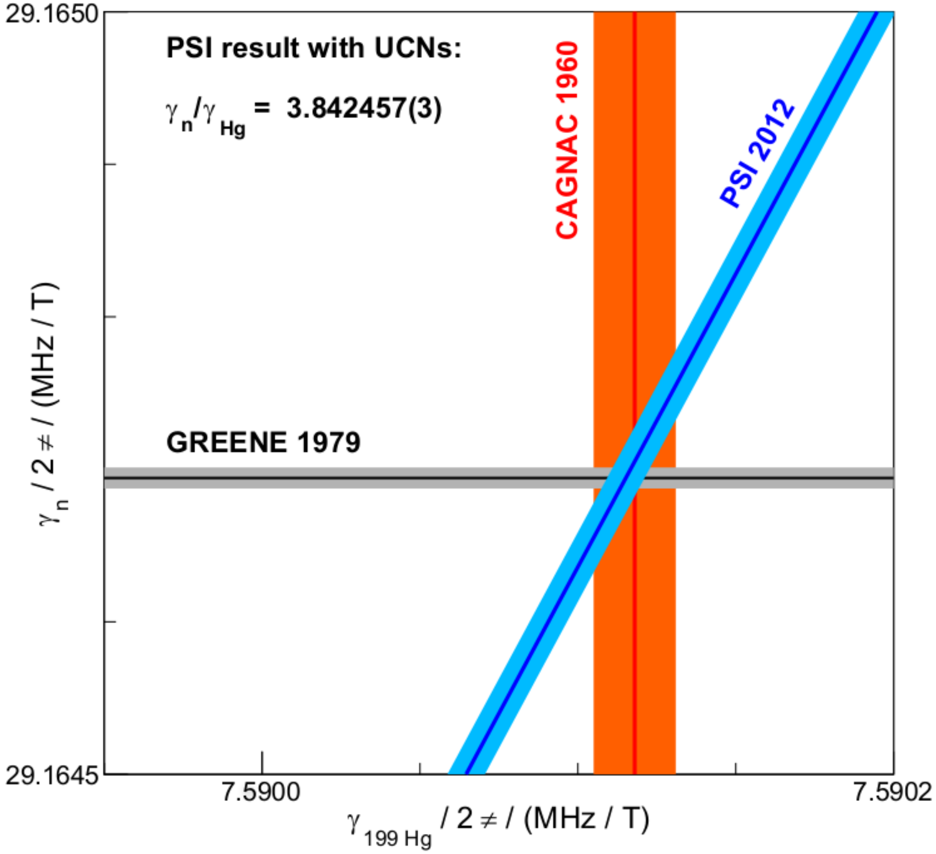
Result: $|a_{\mathrm{exp}}| = 1.122(35) \times 10^{-27}\ e.\mathrm{cm}/\frac{\mathrm{pT}}{\mathrm{cm}}$
$|a_{\mathrm{th}}| = 1.148 \times 10^{-27}\ e.\mathrm{cm}/\frac{\mathrm{pT}}{\mathrm{cm}}$

Available: 10.1140/epjd/e2015-60207-4

"Measurement of a false electric dipole moment signal from ^{199}Hg atoms exposed to an inhomogeneous magnetic field"

$$d_{\mathrm{Hg,th}}^{\mathrm{false}} = \pm \frac{\hbar\gamma^2 D^2}{32\, c^2} \frac{\partial B_z}{\partial z}$$

Neutron to ^{199}Hg magnetic moment ratio



Larmor frequency definition: $f_L = \frac{\gamma}{2\pi} B_0$

The gyromagnetic ratio of the two species reads:

$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}(1 + \delta_{earth} + \delta_{grav} + \cdots)$$

$$\frac{\gamma_n}{\gamma_{Hg}} = 3.8424574(30) \;\; [0.78 \text{ ppm}]$$

Interpretation as a new measurement of whether γ_n or γ_{Hg} at the ppm level

Results in agreement with previous measurement

Available: Physics Letters B 739, 128-132 (2014)

Control of systematics

Effect	Status $[\times 10^{-27}\ e.\text{cm}]$
Direct effects	
Uncompensated B-Drifts	-0.7 ± 1.1
Leakage current	0.00 ± 0.05
$v \times E$ UCN	0 ± 0.1
Electric forces	$0 \pm$ [illegible]
Hg EDM	0.02 ± 0.06
Hg direct light shift	0 ± 0.008
Indirect effects	
Hg Light Shift	0 ± 0.05
Quadrupole difference	1.3 ± 2.4
Dipoles	
At surface	0 ± 0.4
Other dipoles	0 ± 3
Total	0.2 ± 4.0

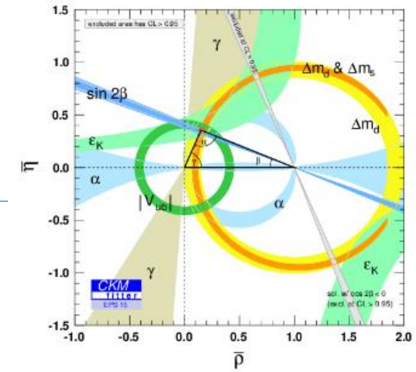
Not up-to-date

Intensive magnetic field mapping

Benefit from external 16 CsM array

Standard models

[Sakharov, 1967]



SCM:

Baryonic number violation
Sphaleron mechanism
[Klinkhamer, 1984]

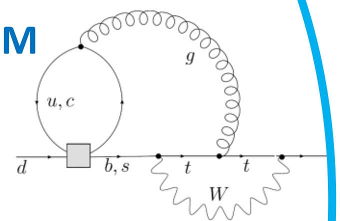
Departure from Thermal Equilibrium

CP violation

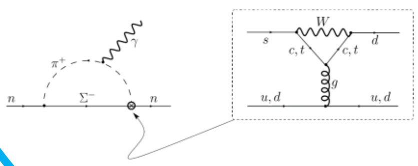
SM weak sector:

K – B mesons decay
K_S & K_L
[Christenson, 1964]

3 loops quark EDM
$d_n \approx 10^{-34}\ e.\mathrm{cm}$
[Khriplovitch, 1986]



Strong penguin diagram
$d_n \approx 10^{-32}\ e.\mathrm{cm}$
[Khriplovitch, 1981]



Very low weak SM sector background!

$$d_n^{SM} \approx 10^{-32}\ e.\mathrm{cm}$$

Strong SM sector predictions unknown

$$\bar{\theta}_{QCD} < 10^{-10}$$

Baryon Asymmetry of the Universe

$$\eta_{CMB} = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-10}$$

Complexity of QCD vacuum
θ_{QCD}
['t Hooft, 1976]

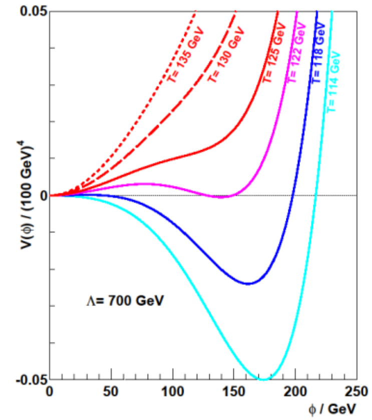
Quark mass matrix
$Arg\ \det\ M_q$
[Jackiw, 1976]

SM strong sector:

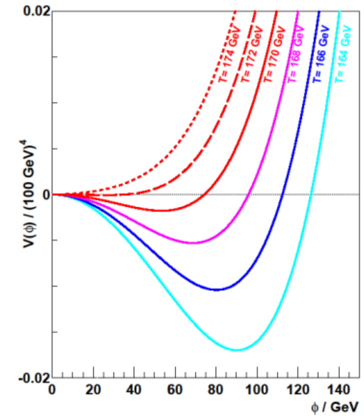
BSM Electroweak Baryogenesis

- **SM EWBG** is already **excluded** :
  m_{H} too high
  δ_{CKM} not large enough

- Adding $\mathcal{O}(6)$ operator $\sim \frac{1}{8\Lambda^2}\varphi^6$ allows strong 1st order EW phase transition
  -> **falsifiable theory**



SM + $\mathcal{O}(6)$



SM only

[Bernreuther, 2002]

- **HOW? :**
  EWBG requires **CP violation at EW scale from BSM physics**
  BSM CP violation phases $\boldsymbol{\delta_{\mathrm{BSM}} > \delta_{\mathrm{CKM}}}$ [Huet, 1994]

-> **new sources** of CP violation best probed by **EDM experiments**

Strong CP problem

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}} + \frac{\bar{\theta}\, g_s^2}{32\pi^2} G \cdot \tilde{G}$$

Dimension 4 operator authorized by TQC
Can exist at 1 loop correction diagrams
Violates CP symmetry

- $G \cdot \tilde{G}$ not a global gauge transformation invariant [Peccei, 2006] -> $U(1)_A$ problem (Weinberg 1975)

- $\bar{\theta}$-term arising from QCD vacuum complexity and quark mass matrix imaginary part ($\bar{\theta} = \theta + \text{Arg}\det M$)

- $\bar{\theta}$-term constrains from nEDM upper bound:

$$d_{\text{n}} \sim e\frac{\bar{\theta} m_{\text{q}}}{M_{\text{n}}^2} \quad \rightarrow \quad \boldsymbol{\bar{\theta} < 10^{-10}}$$

- SM needs non-explained fine tuning or an additional scalar field: the Axion